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EFFECT OF TEXTURE ON THE CHARPY IMPACT ENERGY OF SOME TITANIUM ALLOY PLATE

ANTHONE ZARKADES and FRANK R. LARSON
METALS DIVISION

June 1972

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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13. ABSTRACT

An investigation to determine the anisotropic nature of toughness due to texture in titanium and titanium alloy plate was conducted. Standard Charpy V-notch specimens were machined at ten-degree increments from the rolling to the transverse direction with notch orientation either parallel or perpendicular to the plate surface. Basal pole figures were determined along with impact energy, tensile properties, and microstructure. The study revealed that significant toughness variations can be found in titanium plate as a function of specimen and notch orientation. This impact energy anisotropy can be related to texturing with normal fibering effect being small or absent. An explanation of the toughness variation on a simplified crystallographic slip basis is given. Titanium plate studied includes commercially pure, Ti-6Al-4V, Ti-4Al-4V, Ti-4Al-4Mn, and Ti-8Mn. (Authors)

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INTRODUCTION

The anisotropic nature of the mechanical properties of metals can arise from two sources. The first is related to crystallographic preferred orientation or texture, and the second is due to fibering or elongation of nonmetallic inclusions as it is commonly seen in steel. All mechanical properties are affected to some degree by both types of anisotropy. In the past, when the quality of steel was poor and more nonmetallic stringers were present, a large amount of effort was devoted to studying the anisotropic characteristics of fracturing. More recently, interest has shifted to the effects of preferred orientation upon yielding. Most of this work has centered around the increases in strength which can be expected in biaxial loading. This work on preferred orientation has dealt mainly with yield and flow with very little attention being directed toward fracture or toughness. The basic problem of predicting the effects of texture upon the toughness is extremely difficult and complicated because it includes yield and flow effects. The toughness property can be viewed as the integral of the area under the stress-strain curve. From this it can be seen that the total work or toughness is a function of both the strength levels and the fracture ductility. The problem is a complicated one as the strength level and the fracture ductility are related. The effects of texture on yielding and flow are fairly well understood from the work of Hill[1] and Backofen et al.,[2] yet the quantitative definition of the effects of texture on fracture are illusive and ill defined.

In these situations an experimental program is useful in defining the parameters. It was the purpose of this investigation to determine the anisotropic nature of toughness in titanium and titanium alloy plate where a known texture was present. The Charpy impact specimen was utilized for convenience and because at the level of toughness found in some of the plates, a specimen larger than the plate thickness would be required to determine a valid K_{IC}.

TESTING PROCEDURE

Examination of ten titanium plates as listed in Table I was carried out in this investigation. Basal (0002) pole figures were determined along with impact energy, tensile properties, and microstructure. All tests were conducted at room temperature with the exception of Ti-75A-M230 in which impact energies were also determined at 100, 200, and 300 C. All material was examined in the as-received condition. Plate thicknesses ranged from 0.50 inch to 1.00 inch.

Single-quadrant basal pole figures were determined to describe the crystallographic preferred orientation for each material. The reflection technique described by Lopata and Kula[3] was utilized.

Standard 0.394-inch-square Charpy V-notch impact specimens were machined at ten-degree increments from the rolling direction to the transverse direction. Two notch orientations were examined. One orientation has the specimens notched parallel to the plate surface, and the second orientation has the notch normal to the plate surface or in a through-thickness direction. With ASTM designations for longitudinal and transverse directions, specimens with notches as indicated would be RT, WT and RW, WR. In this form, the first letter indicates the direction the notch is normal to, and the second letter the direction of

Table I. TITANIUM PLATES EXAMINED

Titanium Alloy	Heat
Ti-RC55	5-3285-B
Ti-75A	M230
Ti-75A	L925
Ti-4Al-4V	H8839
Ti-4Al-4V	G8821
Ti-4Al-4V	G8839
Ti-6Al-4V	2804
Ti-RC130B	3210M
Ti-RC130A	A3249B
Ti-RC130A	A3251T

crack propagation (see Figure 1). For the thickest plate examined (1.0 inch), which was the Ti-4Al-4V alloy, Charpy specimens were taken from the top and bottom of the plate. Impact results plotted are an average of these specimens. All Charpy specimens were tested on a 217 foot-pound capacity Mouton pendulum-type machine with a striking velocity of 16.8 feet per second.

Flat tensile specimens were machined from the plates at both the longitudinal and the transverse direction. A 2-inch gage length section and 0.80-inch-diameter pin holes for loading were utilized. Tensile specimen thickness was identical to plate thickness for most cases. Exception to this was the Ti-4Al-4V alloy in which a reduced thickness of 0.[illegible] inch was utilized in the flat tensile specimens. Tensile specimens were tes[illegible] at a strain rate of 0.005 inch per minute on a 120,000-pound hydraulic testing machine. Precision strain measurements for the determination of Young's modulus and Poisson's ratio in both the elastic and plastic zones were obtained by the bonding of 90-degree, 2-element, rosette strain gages to the gage length section of the specimens. The signal from this system was fed to an X-Y-Y' recorder. This procedure produced two curves: a load versus longitudinal strain curve and a longitudinal strain versus transverse curve. A secondary engineering curve was also obtained with the use of an extensometer attached to the tensile specimen. A schematic of this test setup is shown in Figure 2.

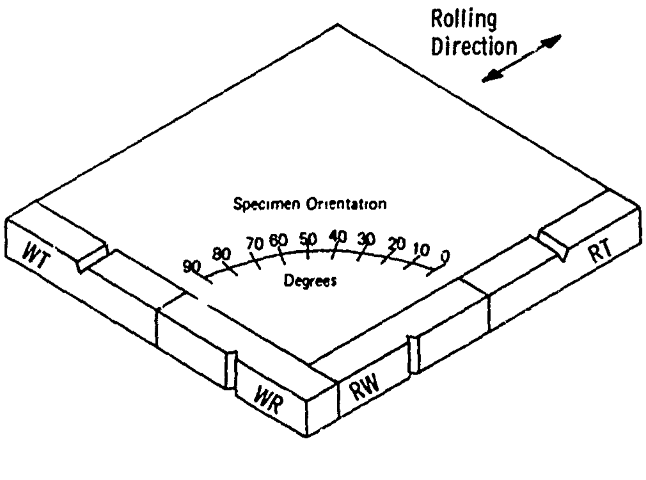


Figure 1. Schematic of Charpy specimen and notch orientation

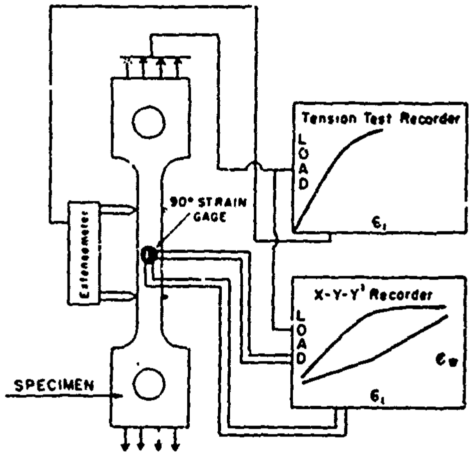


Figure 2. Schematic of tension test apparatus

DISCUSSION OF TEST RESULTS

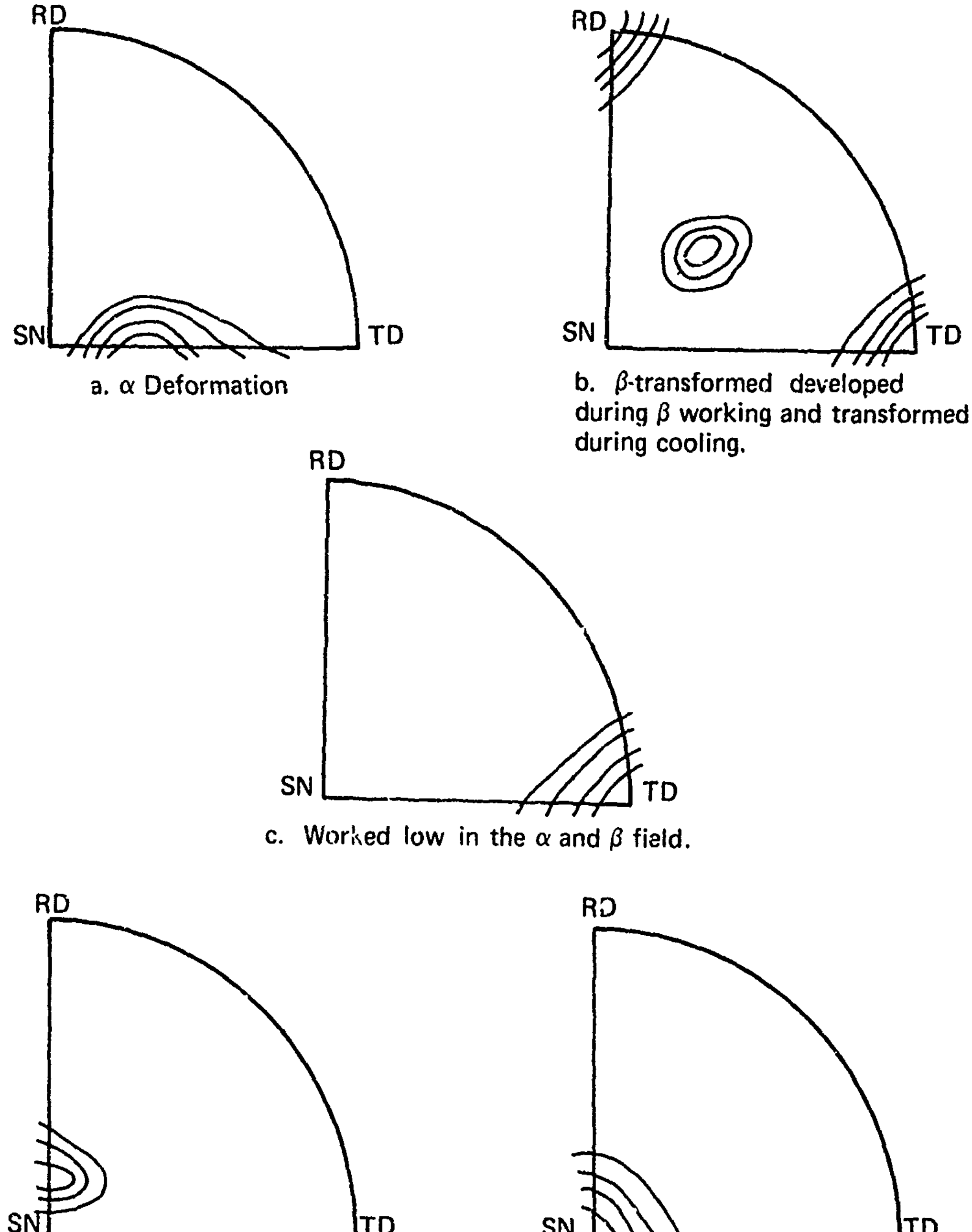
Prior to a detailed discussion of the Charpy impact test results, a brief review of the textures in titanium and its alloys along with a discussion of the anisotropic nature of the mechanical properties would be helpful. An extensive review of preferred orientation in wrought products can be found in an article by Dillamore and Roberts.[4] A number of other reports have been published concerning textures found in titanium.[5-9] The results of these investigations indicate that the textures usually found in sheet or plate can be divided into five major types as schematically illustrated in Figure 3.

It has been found that titanium, which has a hexagonal close-packed structure, develops textures which are well defined and intense. The intense nature of these textures along with the anisotropic characteristics of the titanium lattice gives rise to considerable crystallographic anisotropy of elastic and plastic properties in the polycrystalline mill products. In fact, early process development was aimed at the elimination of anisotropy in the finished product.

If it were desired to demonstrate the variation of elastic and plastic properties as influenced by texture, not all of the textures shown in Figure 3 would be suitable. Since the properties of hexagonal materials are nearly axisymmetric with respect to the c axis of the unit cell then our test samples must be cut at various angles from the c axis for sheet material. Because of difficulty in getting through-thickness test samples for sheet material, this is most easily done with a type texture illustrated in Figure 3c (i.e., where the basal poles lie at or near the transverse direction). Prior work[8] has demonstrated clearly that the elastic and plastic properties do vary in a predictable way and the average tilt of the basal poles from the sheet normal can be calculated from the measurements of elastic and plastic properties. An illustration of property variation with specimen orientation is shown in Figure 4. The high modulus found when the specimen orientation coincides with the basal pole is consistent with data on single-crystal properties.

In order to understand the variation of yield strength, it is necessary to know the deformation modes of titanium. These are shown in Table II. In the case of yielding, the shear stress resolved on the slip plane and in the slip direction is considered as the criterion. It can readily be seen for the texture, shown in Figure 3c, that for a longitudinal test, the largest shear stress would appear on the slip plane and in the slip direction. For a transverse test, the stress axis would coincide with the basal pole and zero resolved stress would appear on the slip plane, and deformation would require twinning and thus a higher yield stress would be measured.[6] The above illustration clearly demonstrates the effect of texture upon the elastic modulus and yield strength.

It would be helpful at this time to define the specimen orientation and crack propagation in relation to the texture. A system is shown in Figure 5 where the strong texture is considered as a single crystal, and only the principal specimen and hexagonal unit cell directions need to be considered. For the first letter, the specimen axis is referred to the pole of the plane which lies parallel to it, and the second letter specifies the direction of crack propagation. P and B stand for prism and basal poles. Furthermore, a and c are conventional hexagonal directions; thus for a titanium texture which had a strong



a. α Deformation

b. β-transformed developed during β working and transformed during cooling.

c. Worked low in the α and β field.

d. Worked high in the α and β field and when retained $\beta < 15\%$.

e. "Ideal" α deformation of Ti-4Al, Ti-0.55 Cu, round rolled Ti-6Al-4V.

Figure 3. (0002) Texture types evident in various titanium sheet and plate

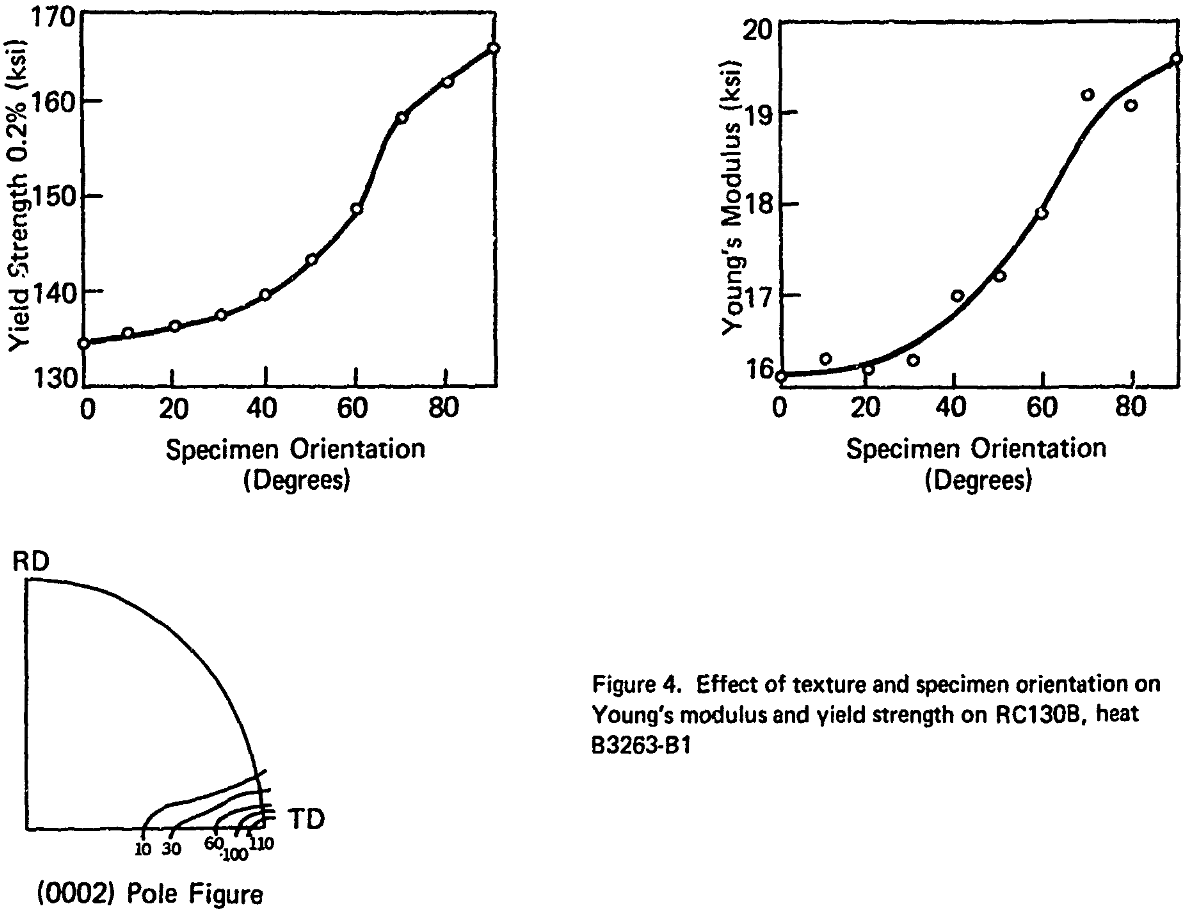


Figure 4. Effect of texture and specimen orientation on Young's modulus and yield strength on RC130B, heat B3263-B1

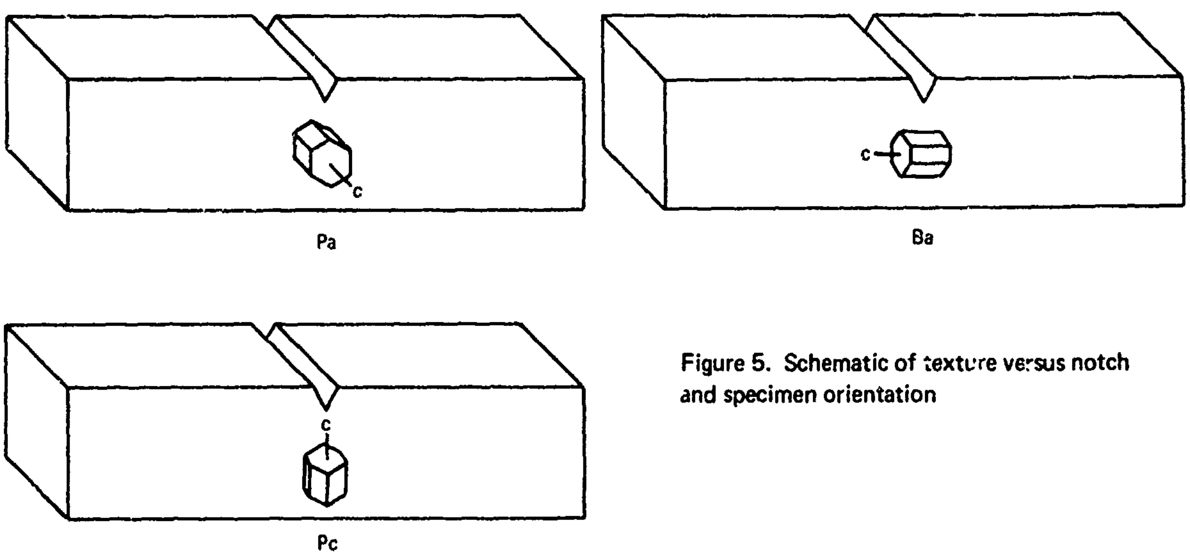


Figure 5. Schematic of texture versus notch and specimen orientation

Table II. DEFORMATION MODES OF TITANIUM

TITANIUM SLIP MODES (ALL IN $[11\bar{2}0]$ DIRECTION)[a]

PLANE	DESIGNATION	COMMENTS
$(10\bar{1}0)$	prism	lowest critical resolved shear stress
$(10\bar{1}1)$	pyramidal	highest critical resolved shear stress
(0001)	basal	intermediate critical resolved shear stress

TITANIUM TWINNING MODES*

TYPE†	K_1	n_1	K_2	n_2	SHEAR	COMMENTS	REF
1	$(10\bar{1}1)$	$[10\bar{1}2]$	$(10\bar{1}3)$	$[30\bar{3}2]$	0.100	compression parallel to c axis	b
2	$(10\bar{1}2)$	$[\bar{1}011]$	$(10\bar{1}\bar{2})$	$[10\bar{1}1]$	0.189	tension parallel to c axis	c
3	$(11\bar{2}1)$	$[\bar{1}\bar{1}26]$	(0001)	$[11\bar{2}0]$	0.638	tension parallel to c axis	c
4	$(11\bar{2}2)$	$[11\bar{2}\bar{3}]$	$(11\bar{2}\bar{2})$	$[11\bar{2}3]$	0.957	compression parallel to c axis	c
5	$(11\bar{2}3)$	$[\bar{1}\bar{1}22]$	(0001)	$[11\bar{2}0]$	0.914	tension parallel to c axis	c
6	$(11\bar{2}4)$	$[\bar{2}\bar{2}43]$	$(11\bar{2}\bar{4})$	$[22\bar{4}3]$	0.468	compression parallel to c axis	c

*Here K_1 is the composition or twinning plane, n_1 is the direction of shear in the twin plane, K_2 is the second undistorted plane in the twin, and n_2 is the direction of intersection of the plane of shear with K_2.

†Type 1 observed only at high temperature; types 4, 5, and 6 increase with decreasing temperature.

[a] McQuillan, A. D., McQuillan, M. K., *Titanium*, Buttersworth, 1956

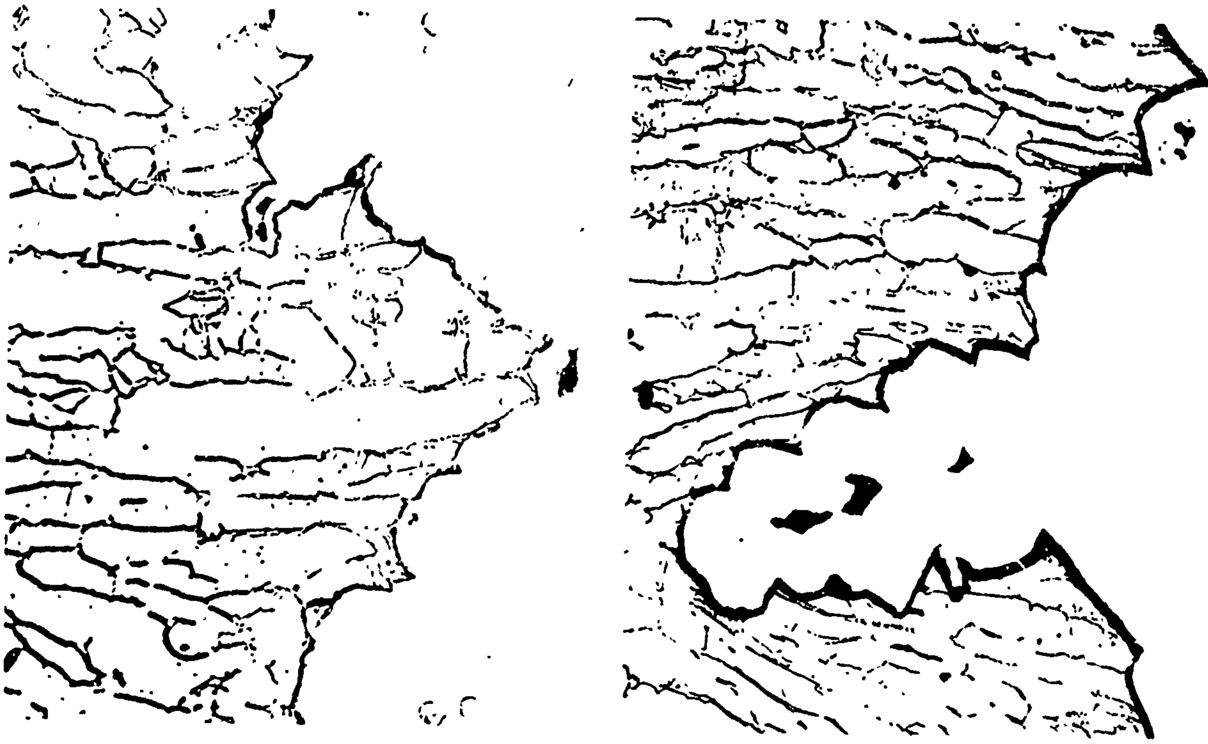
[b] Paton, N. E., Backofen, W. A., Trans AIME 245, 1969, p. 1369

[c] Hall, E. O., *Twinning*, Buttersworth, 1954

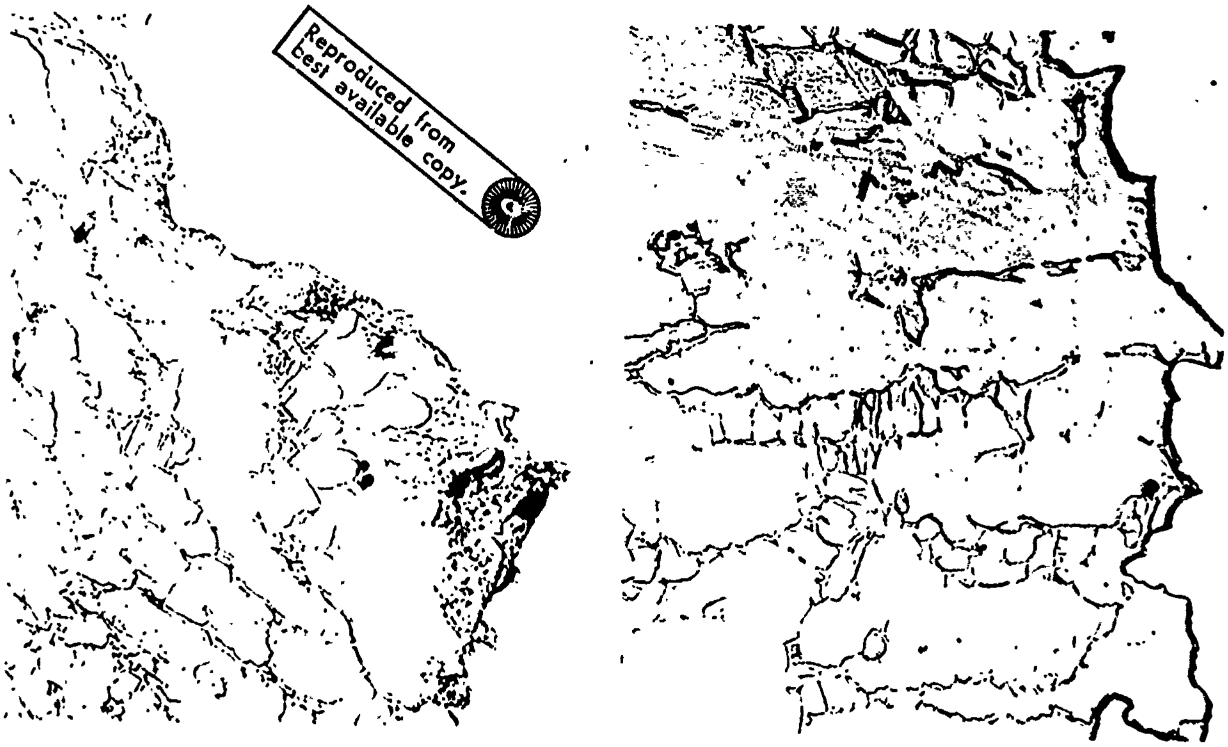
concentration of basal poles in transverse direction, the $(10\bar{1}0)$ poles usually are strongly concentrated in the rolling direction so that a specimen would have a crystallographic or texture designation of Ba.

Since we are primarily concerned about the effects of texture it was necessary to rule out the effect of fibering. Although not completely conclusive, the variation of toughness caused by fibering can be detected by the metallographic observations of delaminations associated with the fracture surfaces.[10] The effect of an elongated second phase can also be evaluated in this manner to a lesser degree. A large number of fracture samples were studied, and delaminations of the type associated with mechanical fibering were not found in the magnitude as described by English.[10] There also did not seem to be much preferential fracture path associated with the elongated alpha-beta duplex structures found in some of the alloys. Some typical fracture paths are shown in Figure 6.

In addition, the Charpy energies did not show the anisotropy difference for the WT and WR orientation normally attributed to mechanical fibering or elongated grain structure. This will be discussed later in the report. Analysis of the data indicate that Charpy impact fractures can be categorized into two general types, brittle and ductile. In the case of brittle fracture (less than 10 foot-pounds) very little anisotropy of toughness was found. See Figures 7 through 11.



0° Notched parallel to plate surface 90°



0° Notched perpendicular to plate surface 90°

Figure 6. Typical fracture path of Charpy V-notched Ti-4Al-4V, H8839. Mag. 1000X

Orien-tation	Thick (in.)	Yield Strength (psi)		Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
		0.1%	0.2%					
L	0.685	55,800	56,900	77,100	36.5	17.6	0.337	0.374
T	0.686	67,100	70,300	83,400	34.5	17.4	0.353	0.611

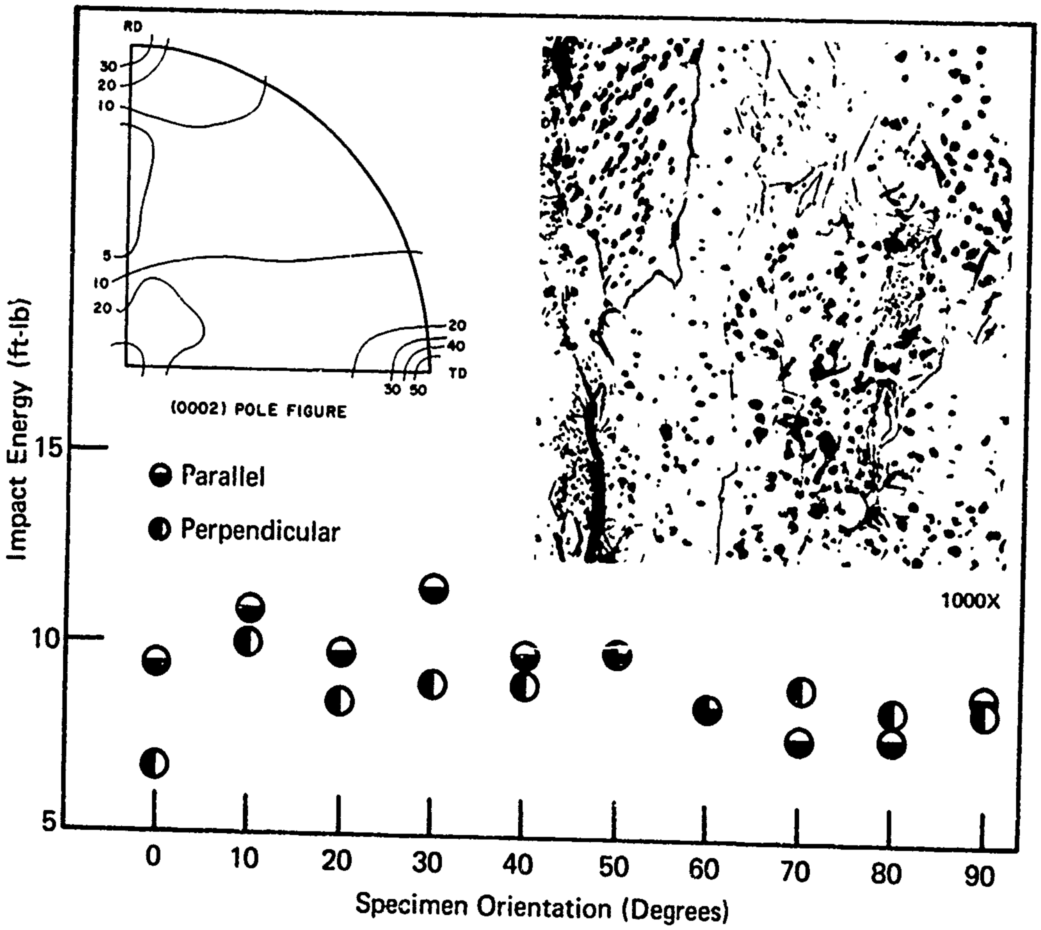


Figure 7. Typical test data for RC55-5-3285-B

Orientation	Thick (in.)	Yield Strength (psi) 0.1%	Yield Strength (psi) 0.2%	Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
L	0.516	56,200	59,700	74,400	31.0	17.8	0.413	0.735
T	0.516	61,600	64,300	72,900	32.0	18.9	0.421	0.818

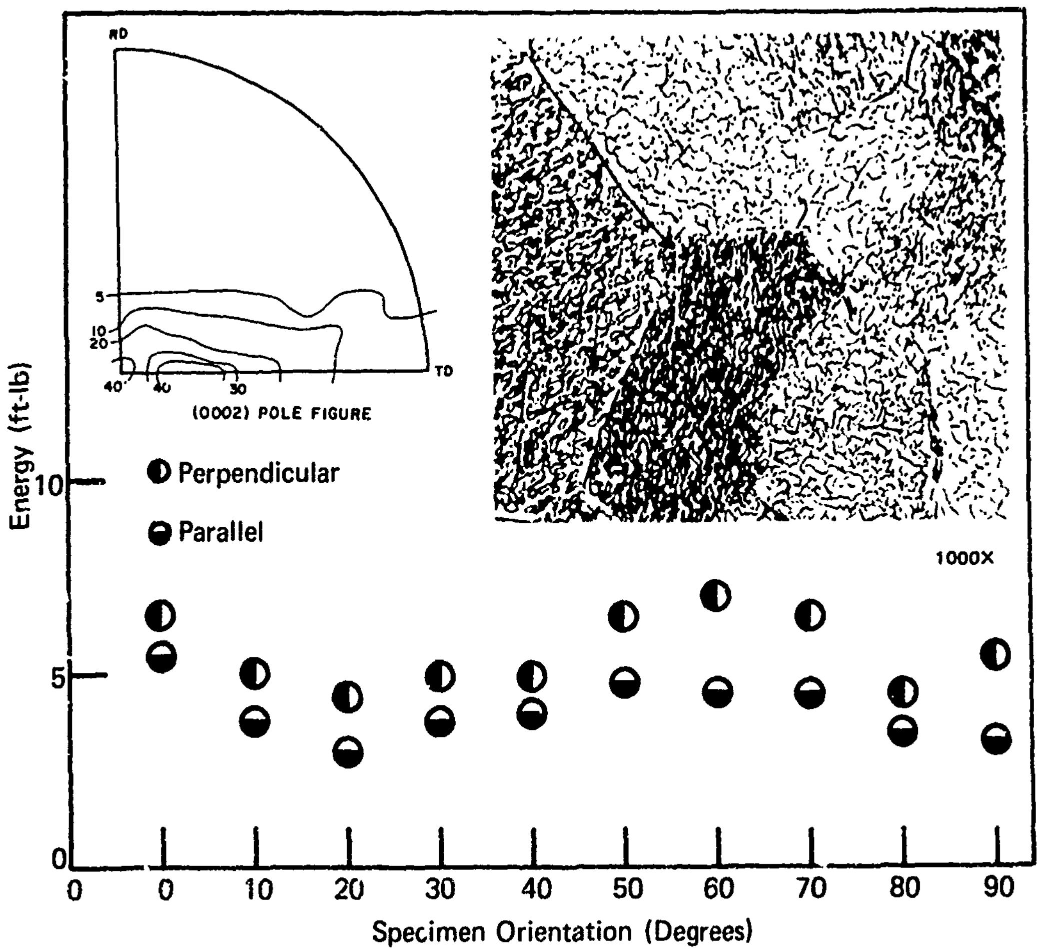


Figure 8. Typical test data for 75A-M230

Orien-tation	Thick (in.)	Yield Strength (psi) 0.1%	0.2%	Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
L	0.443	59,600	60,900	79,500	35.5	15.0	0.400	0.681
T	0.443	66,200	68,000	77,500	31.5	16.7	0.393	0.857

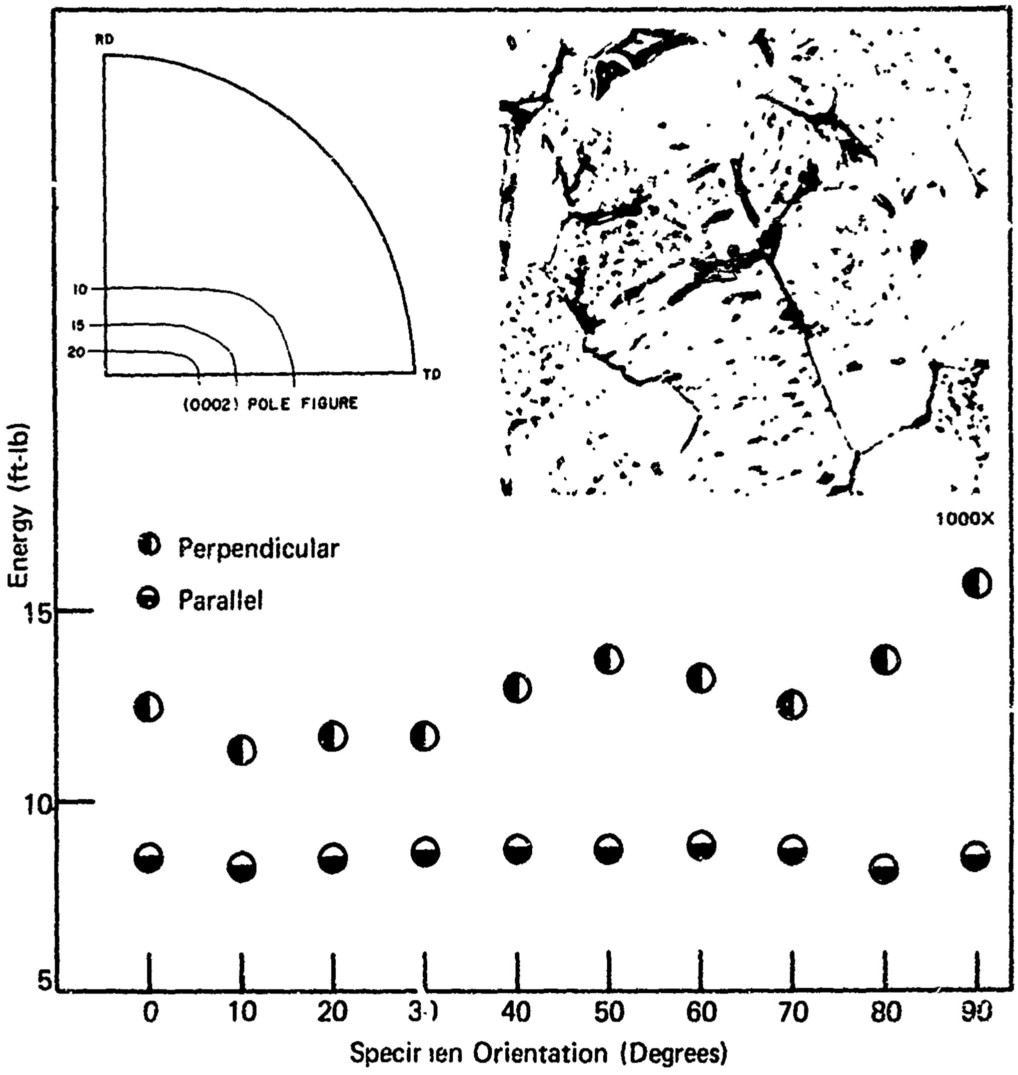


Figure 9. Typical test data for 75A-L925

Orien-tation	Thick (in.)	Yield Strength (psi)		Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
		0.1%	0.2%					
L	0.502	130,800	132,400	141,600	10.5	16.9	0.322	0.433
T	0.502	*	*	*	*	*	*	*

*Specimen broke in pinhole.

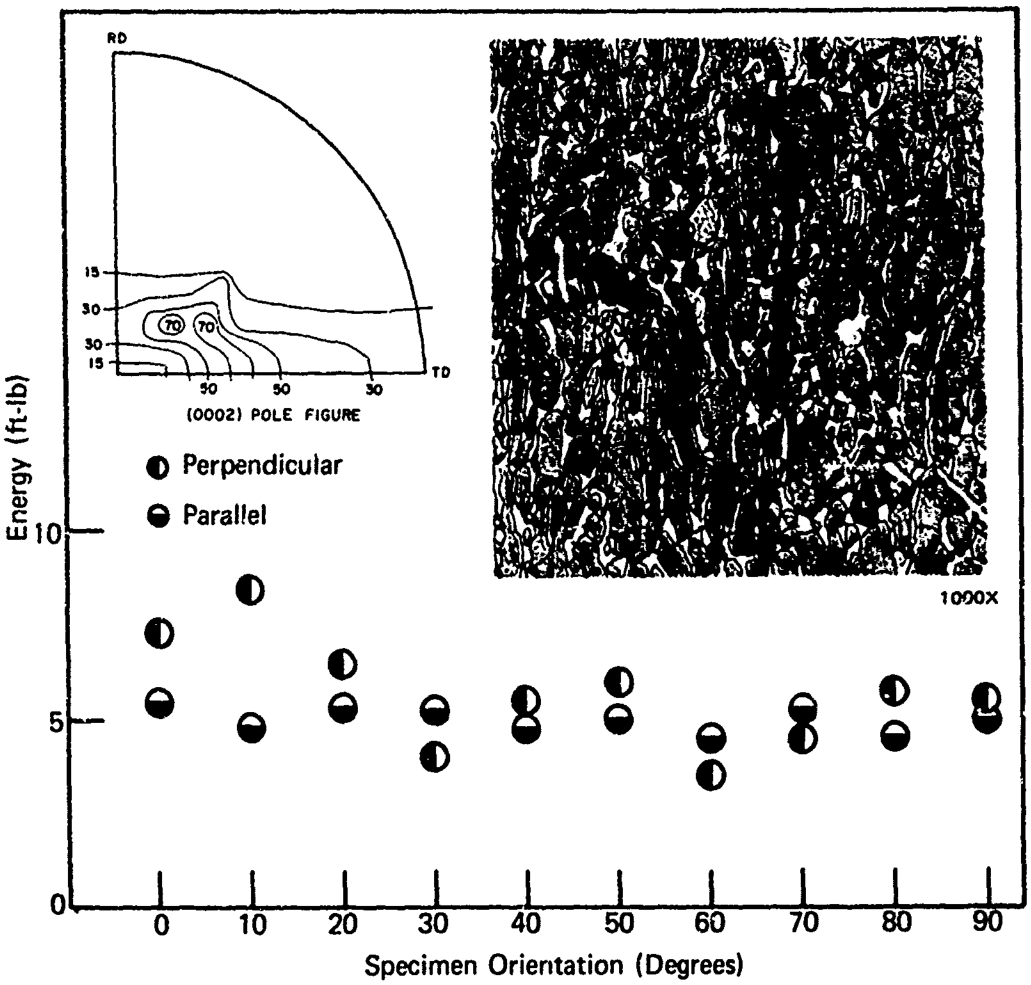


Figure 10. Typical test data for RC130A-A3249B

Orientation	Thick (in.)	Yield Strength (psi)		Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
		0.1%	0.2%					
T	0.532	116,500	119,100	129,300	10.0	17.9	0.314	0.357
L	0.528	103,400	109,800	122,300	28.0	17.5	0.286	0.244

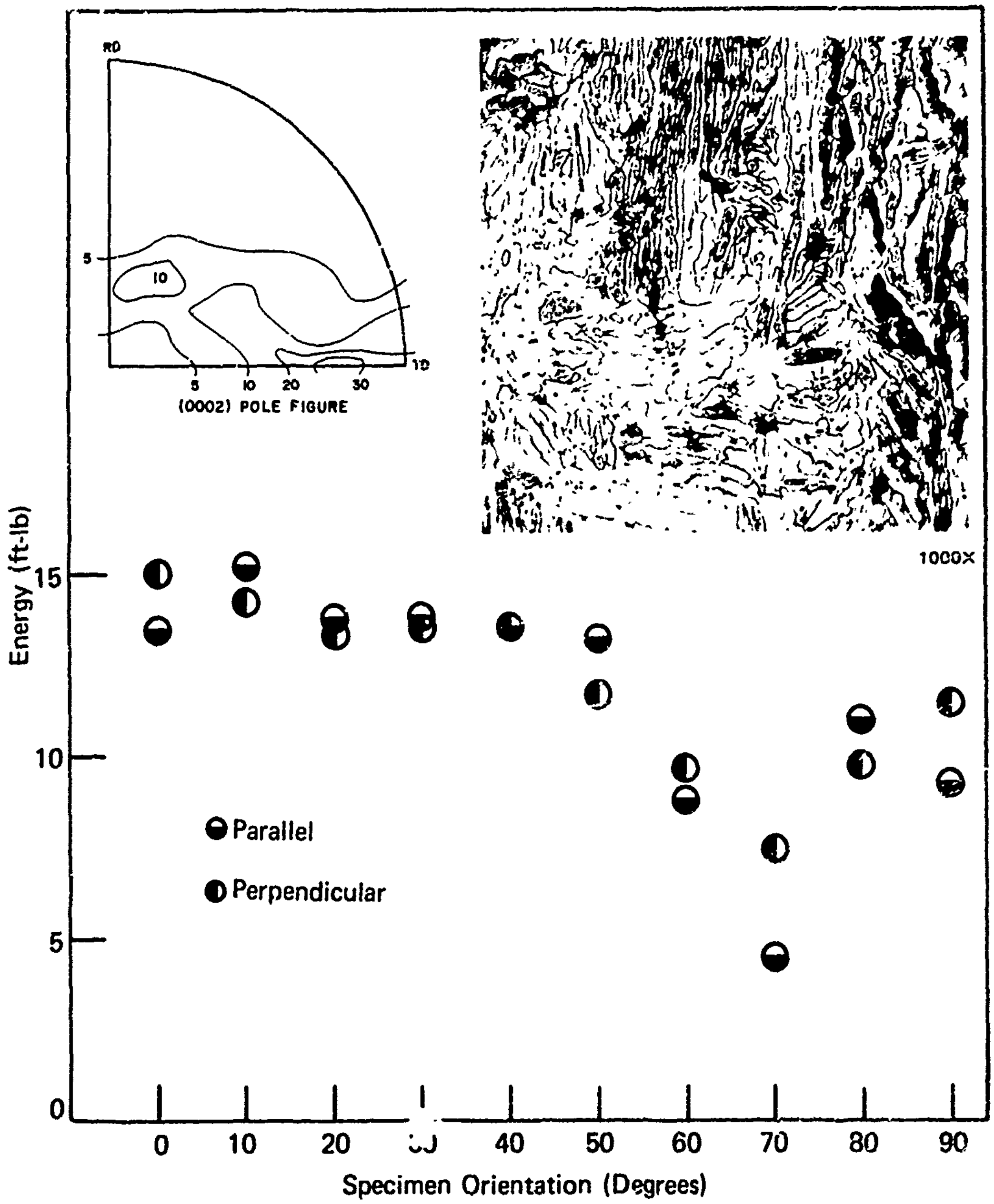


Figure 11. Typical test data for RC130A-A3251T

Thus it appears from this preliminary observation that the anisotropy of Charpy impact properties is related to plastic flow anisotropy. One of the most dramatic cases found was for the Ti-4Al-4V alloy, heat H8839, Figure 12, and other examples are shown in Figures 13 to 16. For heat H8839 the RW and WR specimen orientations gave about 25 foot-pounds. The WT orientation was also low at about 35 foot-pounds. However, the RT results were three times as high or about 75 foot-pounds. These results can be explained if we examine the texture orientation and its ability to plastically deform. From a texture standpoint, the highest energy-absorbing orientation are those with a Pa designation. Considering the fact that slip occurs in the $[11\bar{2}0]$ direction, it can be seen that the Pa orientation would be the "softest" and hence the greatest plastic deformation would be allowed; for the other orientation, either $(11\bar{2}2)$ or $(10\bar{1}2)$ twinning would be required for deformation. Subsequent to the twinning, the lattice reorientations would not be favorable for slip.

The high toughness of the Pa orientations unfortunately was not demonstrated for "ideal" textures in this program for they were generally brittle (Figure 9). However, they were clearly shown in the work of Hatch,[11] see Table III. For ideal textures, the tough orientation (Pa) would occur for all edge-notched specimens (RW and WR).

The effect of texture upon the toughness transition caused by varying temperature can be seen in Figure 17.[12-13] The data is for Zircaloy 2 which has similar deformation modes to titanium. This rolling schedule was found to produce a nearly ideal texture, thus the RW or WR orientation specimen would have a texture orientation of Pa and the RT and WT would have a Pc orientation. The argument is that for the soft Pa orientation plastic flow occurs and high energy is absorbed. For the Pc orientation higher levels of strength are required to induce flow and then fracture occurs at lower strains, resulting in a less tough condition. As the temperature is raised, the Pc orientation becomes tougher due to a relaxation of the higher stresses by the introduction of c plus a slip or slip with a nonbasal vector.

In order to verify the effect of texture on the transition temperature, a series of specimens were cut from Ti-75A. heat M-230. This plate had a texture with a basal pole intensity near the plate normal with little transverse spre The tough Pa specimen orientation would correspond to the through-thickness notch orientation. From examination of data at several test temperatures, it can be seen that the transition temperature is lower and the toughness is higher for the Pa specimen orientation (Figure 18). These results are in agreement with the results for Zircaloy 2.

Table III. IMPACT AND R VALUES FOR Ti-4Al, 0.5-INCH PLATE[11]

O_2 (%)	ROLLING TEMP. (°F)	TEST DIRECTION	CHARPY V-NOTCH IMPACT ENERGY (FT-LB)		R
			EDGE NOTCH	FACE NOTCH	
0.21	1700	L	RW 63.5	RT 17.5	5.1
0.21	1700	T	WR 67.0	WT 17.3	9.5

Orien-tation	Thick (in.)	Yield Strength (psi) 0.1%	Yield Strength (psi) 0.2%	Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
L	0.460	93,500	97,400	110,700	19.0	16.5	0.242	0.188
T	0.475	99,600	102,500	115,600	21.5	16.2	0.246	0.226
L	0.472	112,300	114,800	119,100	17.0	17.7	0.250	0.369
T	0.507	118,300	120,700	127,400	20.5	19.7	0.300	0.321

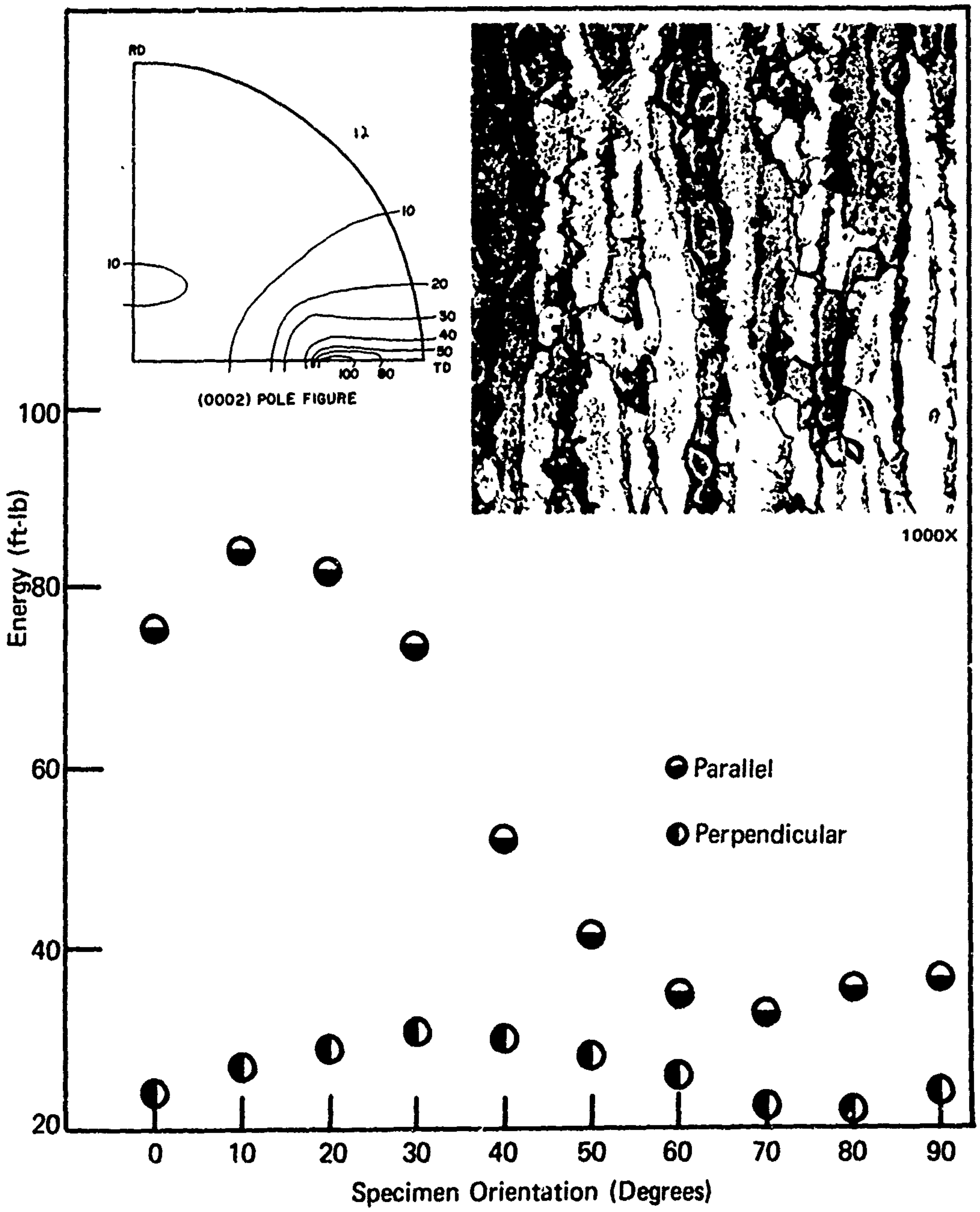


Figure 12. Typical test data for 4Al-4V H8839

Orien-tation	Thick (in.)	Yield Strength (psi)		Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
		0.1%	0.2%					
T	0.282	115,000	115,400	117,500	15.5	18.6	0.313	0.429
L	0.281	92,700	94,500	105,600	19.0	15.1	0.242	0.153

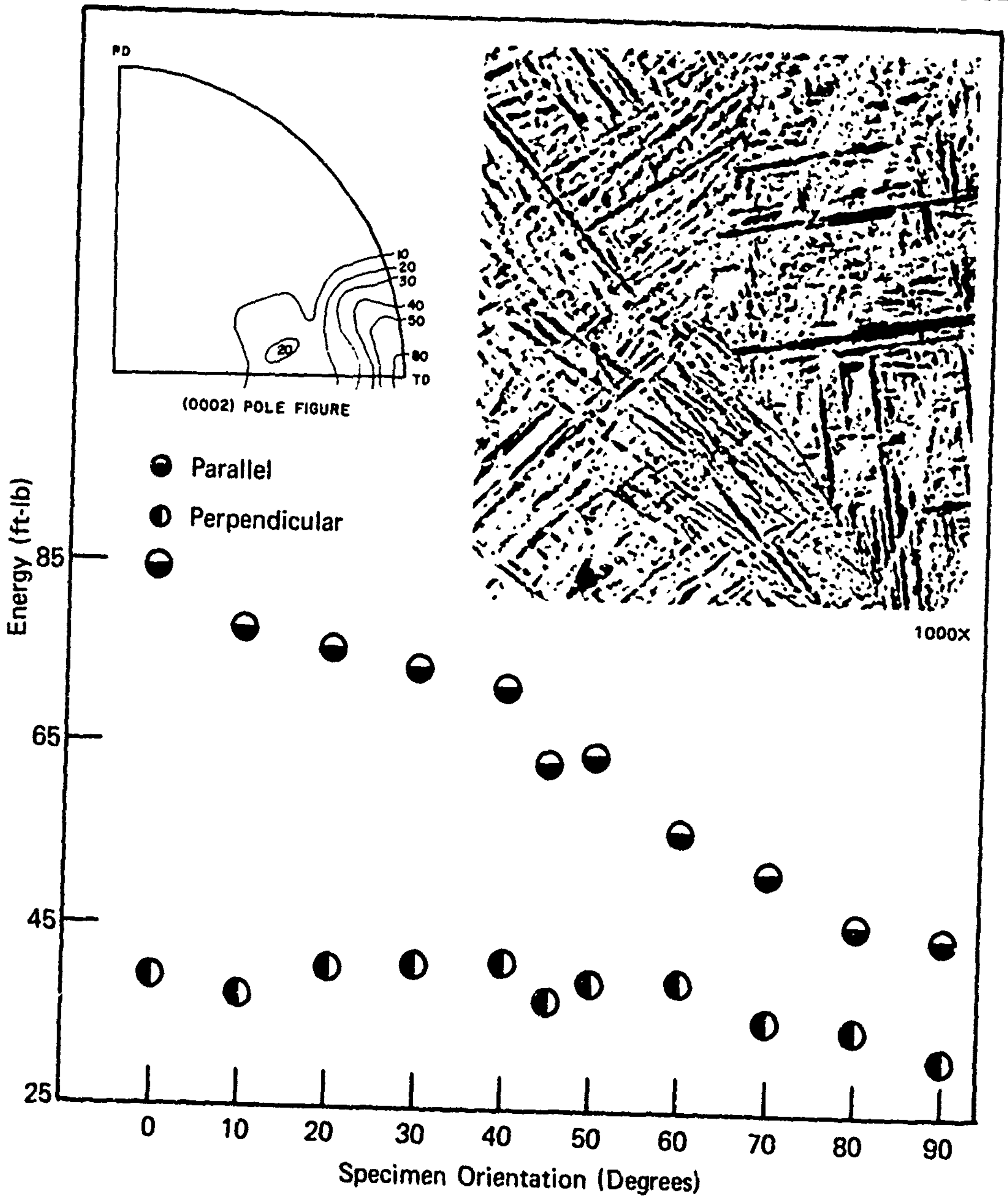


Figure 13. Typical test data for 4Al-4V G8821

Orientation	Thick (in.)	Yield Strength (psi) 0.1%	Yield Strength (psi) 0.2%	Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
L	0.359	100,600	101,200	109,500	21.0	16.3	0.258	0.154
T	0.358	119,300	119,300	120,400	18.5	18.6	0.306	0.404

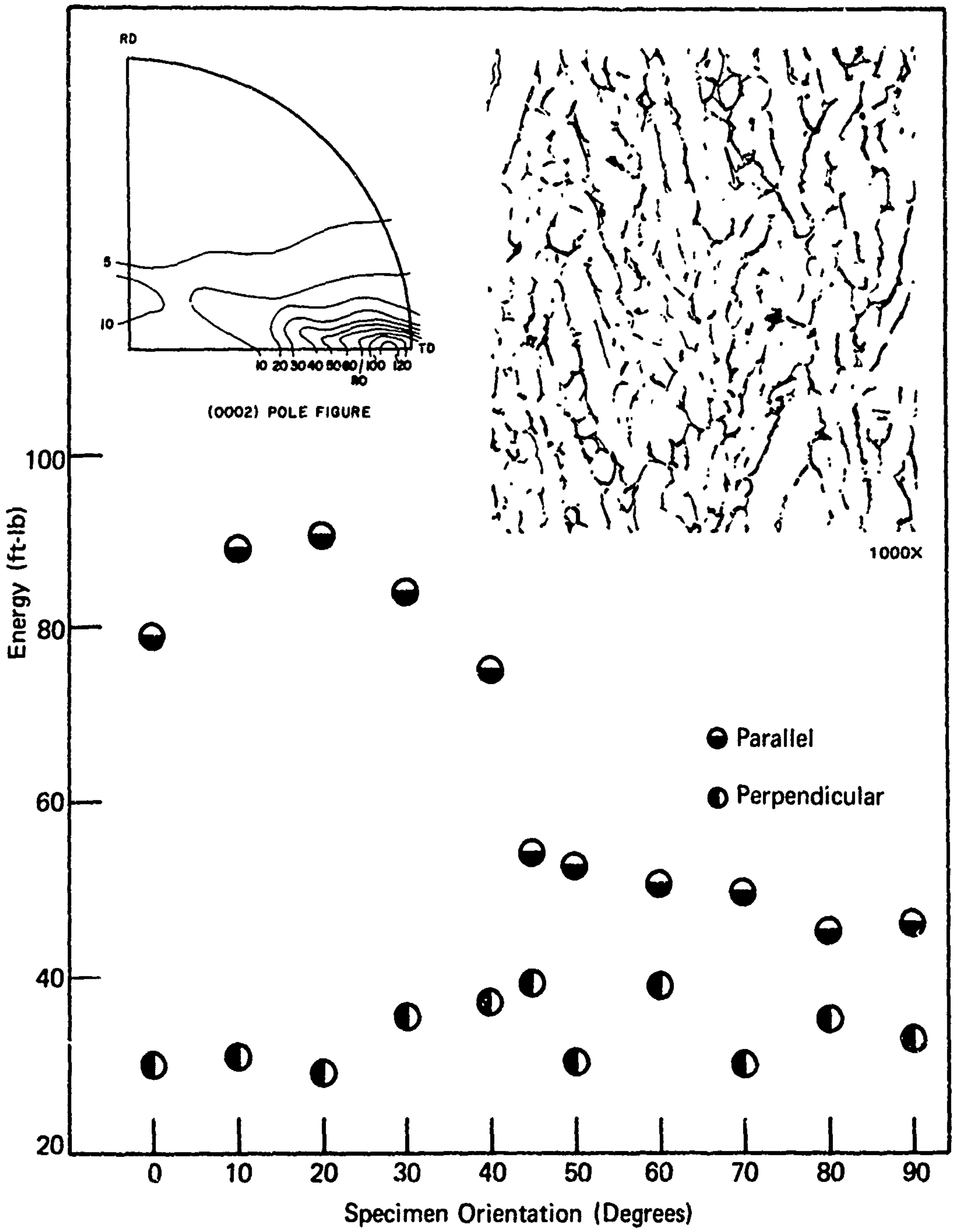


Figure 14. Typical test data for 4Al-4V G8839

Orien-tation	Thick (in.)	Yield Strength (psi)		Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
		0.1%	0.2%					
L	0.525	120,000	122,200	130,200	14.0	16.3	0.257	0.250
T	0.527	132,100	134,700	140,800	10.0	19.7	0.300	0.444

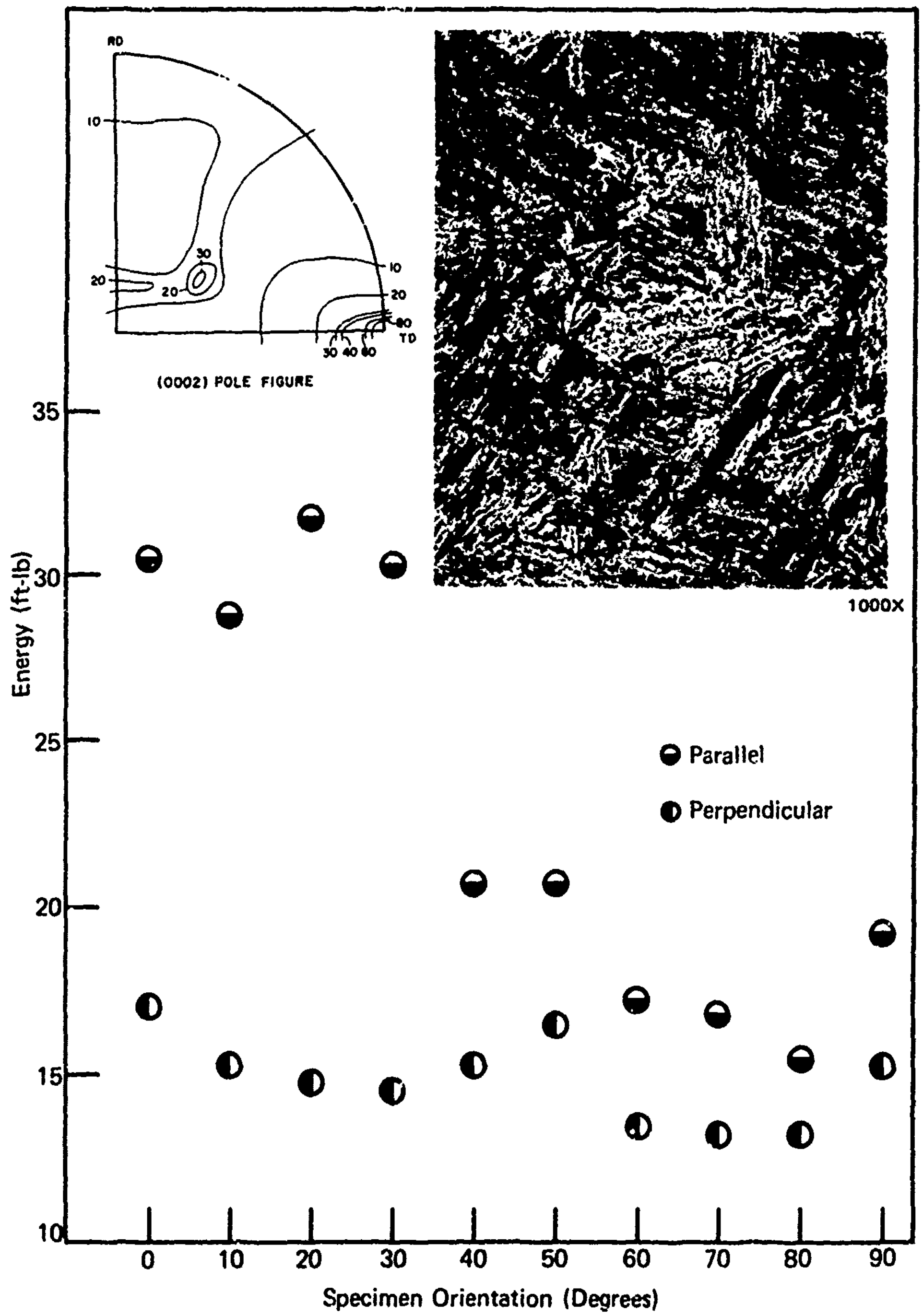


Figure 15. Typical test date for 6Al-4V 2804

Orien-tation	Thick (in.)	Yield Strength (psi)		Tensile Strength (psi)	Elon. %	E x 10^6 (psi)	μ_E	μ_P
		0.1%	0.2%					
T	0.492	74,000	76,000	87,000	28.0	19.9	0.360	0.632
L	0.489	67,500	83,800	83,800	33.0	18.3	0.339	0.516

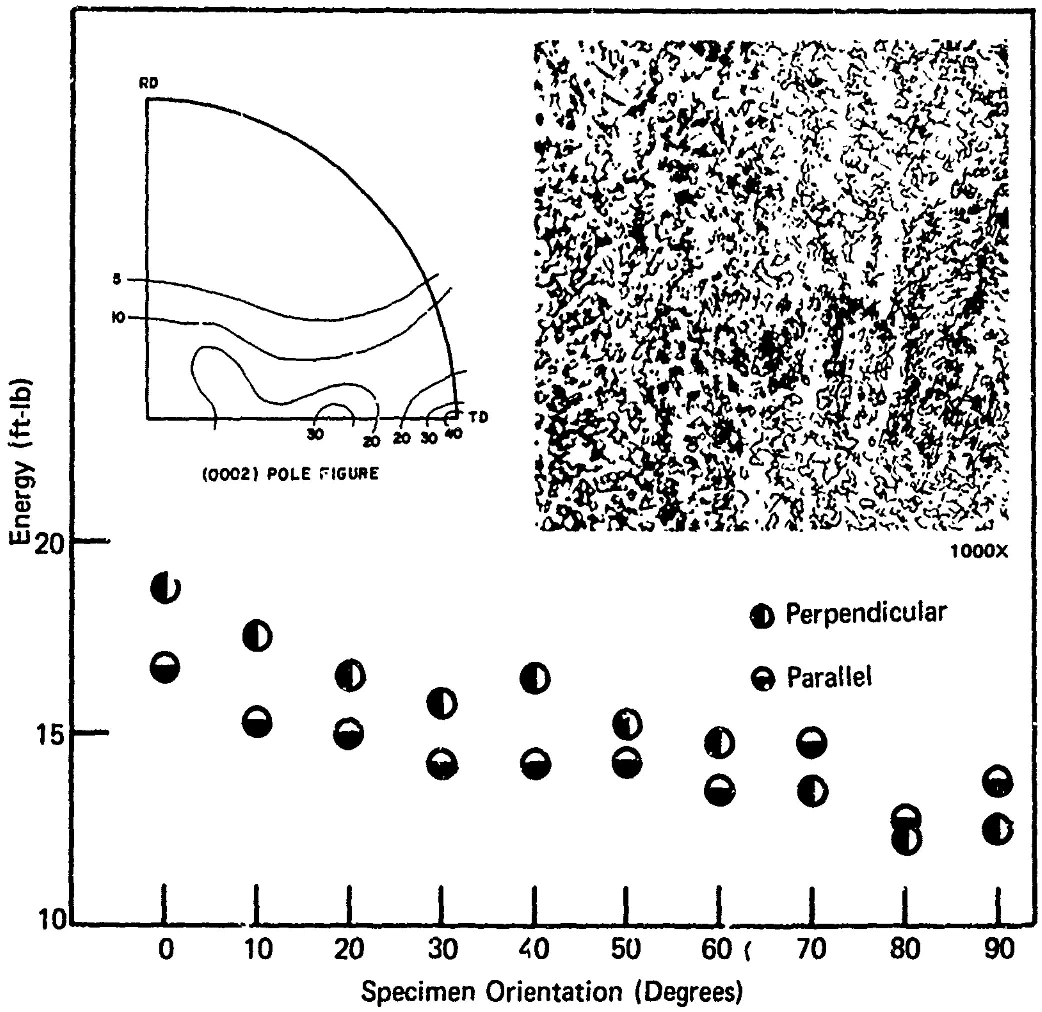


Figure 16. Typical test data for RC130B - 3210M

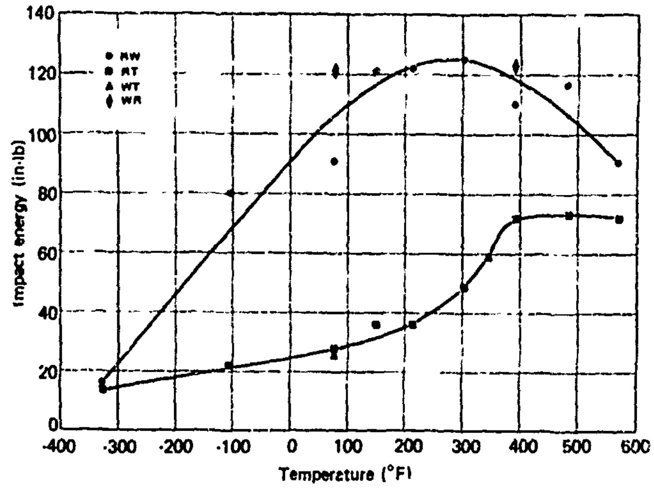


Figure 17. Impact energy curves for schedule 8 Zircaloy-2. Shedule 8: α worked, 70 percent low α reduction. Ref. 12

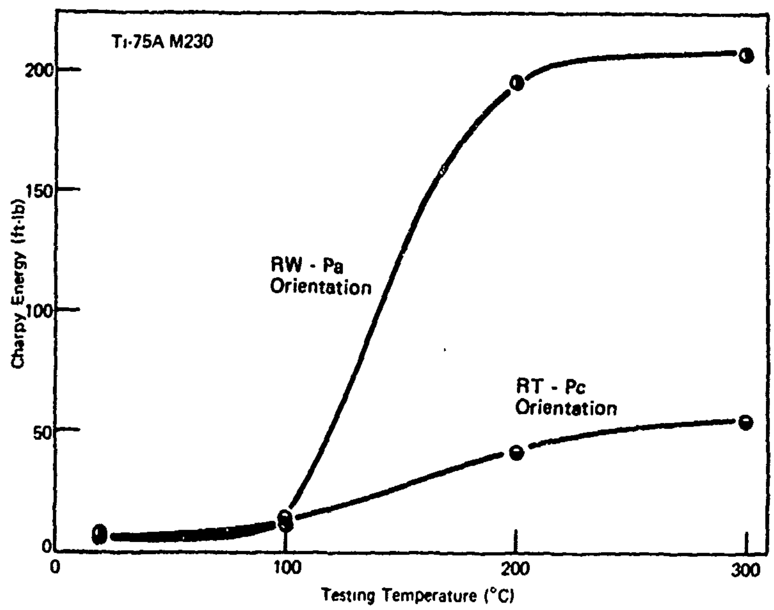


Figure 18. Effect of texture on the transition temperature

A better understanding of the relationship between plastic deformation and fracture can be had from studying Figure 19 and References 14 and 15. At high temperatures the critical resolved stress for $(10\bar{1}0)$ $[11\bar{2}2]$ slip is low and the specimen in a Pa orientation (Figure 19a) is favorable for this type of deformation. As the temperature is lowered, the critical resolved stress for $(10\bar{1}0)$ $[11\bar{2}2]$ slip rises until $\langle 11\bar{2}2\rangle$ twinning begins, then microcracks are formed at the twin-matrix interface and brittle fracture ensues. For the Pc (Figure 19b) specimen orientation a similar behavior is apparent; however, due to the plane strain constraints at the base of the notch, a higher temperature is needed for plastic flow and high toughness. Predictions are for large compressive deformations at the back side of the specimen. Finally, the Ba orientation specimen is not favorably oriented for slip or any of the known slip systems since the stress is perpendicular to the $[11\bar{2}2]$ direction. In this case $(10\bar{1}2)$ twinning probably

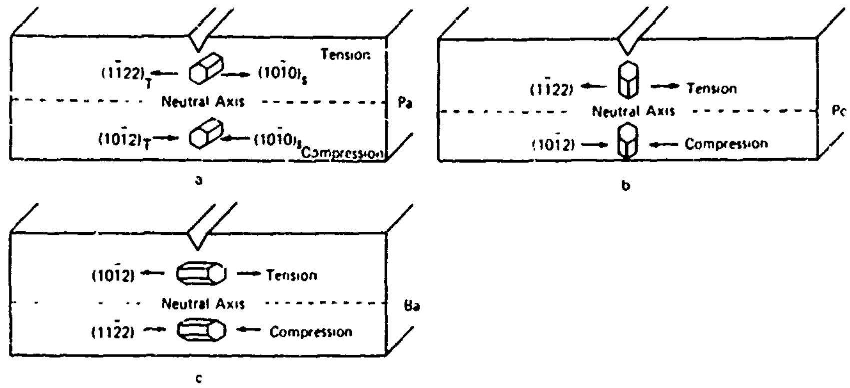


Figure 19. Specimen deformation modes and texture orientation

occurs, and the reoriented matrix would now be favorably oriented for $(11\bar{2}2)$ twinning and susceptible to fracture (Figure 19c). The above comments are, of course, highly speculative and require further research. This discussion, however, does provide a simple model for the description of texture and its influence on toughness and this beginning of understanding should allow us to utilize textures to produce high toughness materials.

CONCLUSIONS

1. A significant toughness variation has been found in titanium and titanium alloy plate as a function of specimen and notch orientation.

2. This toughness variation can be related to the texture of plate with the normal fibering effect being small or absent.

3. This toughness variation can be explained on a simplified crystallographic slip basis where plastic flow predominates.

4. For brittle fracture, the effect of crystallographic texture was not evident.

5. The texture has an influence on the toughness transition with the lower transition temperatures being tied to a specific texture orientation.

RECOMMENDATIONS

The toughness variation caused by the relation between specimen orientation and texture should be further explored. Other factors that affect the toughness in titanium and its alloys should be reexamined in light of these findings, to determine the influence of texture. A basic study of the role of slip and twinning along with brittle fracture should also be studied.

Since it has now been demonstrated that texture dramatically affects the elastic, plastic, and toughness properties, programs should be initiated to determine what other properties will be affected. Some prime candidates are K_{IC} fatigue (including crack initiation and propagation), stress corrosion, and creep resistance.

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